Attempts at Ion Cyclotron Heating
In a Toroidal Octupole

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ABSTRACT

A 100kW, 1MHz oscillator has been constructed to produce 300μsec rf pulses for ion cyclotron heating in a toroidal octupole. Various methods of coupling to the plasma have been tried. By driving the hoops electrostatically with respect to the wall at 2 kV rms, some electric field (~10V/cm) is observed in the interior of the plasma, but the large fields at the boundary result in severe plasma loss during heating. A three phase system has been developed to drive rf currents into the three supports on each hoop. The rf hoop current of ~100 amps produces a field modulation $\Delta B/B \sim 10^{-3}$, and electric fields of ~1V/cm. For the plasma densities used, magnetic probes indicate complete penetration of the rf field into the plasma. Calculations indicate an expected average heating rate of ~0.1eV/μsec. Ion saturation current to a probe on the B=0 axis shows a slight increase after heating, providing some experimental evidence for ion heating.

Electron Cyclotron resonance heating has proved so successful in multipoles that it is tempting to try to extend the technique to lower frequencies in an attempt to resonantly heat the ions in the plasma. This program is difficult for two reasons. The first is that high density plasmas tend to exclude low frequency electric fields, and the second is that since the free space wave length at the ion cyclotron frequency is much larger than the cavity dimensions, it is difficult to get a good impedance match between the rf oscillator and the cavity.

Nevertheless, a 100 kW, 1 MHz oscillator was constructed that could be pulsed on for up to 300 μsec. Various methods of coupling the rf to the plasma were tried. By modulating the current in the primary of the transformer used to excite the hoops, the magnetic field could be varied by one part in 10^4, producing electric fields of about .1 V/cm. The synchrotron gap could be driven directly, but the impedance is very low because of the small leakage inductance of the transformer, and no improvement was noted. The B_θ gap was tuned to resonance at 1 MHz using a bank of mica capacitors, but the gap was not adequately insulated for the rf voltage. This method will be tried again in the future with better insulation. The oscillator was used to amplitude modulate a 10 cm magnetron in the hope that some non-linear behavior of the plasma would demodulate the microwaves and produce the desired low frequency fields in the plasma. Kuswa has reported preliminary results using this method.[1]

The two methods that were studied in the most detail are outlined in fig. 1. The simplest method consists of driving the hoops electrostatically with an rms voltage of 2 kV with respect to the cavity walls. The other method consists of driving currents through the hoops by applying three phase rf to the three supports on each hoop. The three phase is produced with delay lines, and the load is made to look resistive by adding capacitors which tune the circuit to resonance. This electromagnetic drive system produces rf hoop currents of about 100 amps and electric fields approaching 1 V/cm. The fundamental difference between the two systems is that the electrostatic drive produces electric fields by creating potential gradients, while the electromagnetic drive produces electric fields by a time changing magnetic vector potential. The first method produces considerably larger electric fields in the absence of plasma, but the second method is more effective in penetrating a plasma at high density.

Figure 2 shows a plot of the amplitude of the floating potential oscillation between the hoop and the wall when the hoop is driven electrostatically. The electric field is smallest where the density is highest and largest at the boundaries of the plasma. The potential distribution is in qualitative agreement with a theoretical model of a dielectric plasma in a non-uniform magnetic field.[2]

The electric field at $\psi = 0$ was measured as a function of plasma density using a radial double capacitance probe, and the result is shown in the lower part of Figure 3. There is a lot of scatter in the data points, but the electric field is clearly attenuated at high densities.

A microwave produced plasma was used to obtain these data since the gun injected plasma could only produce densities up to about 10^9 cm^{-3}. The attenuation is in agreement with a simple model that treats the plasma as a dielectric medium. The model predicts an electric field of the form

$$E = \frac{E_o}{1 + n/n_c},$$

where n_c is the density at which the low frequency dielectric constant,

$$\varepsilon = \varepsilon_o + \frac{nM}{B^2}$$

is equal to $2\varepsilon_o$.

For the electromagnetic drive, the rf magnetic field was measured at the same place using a small magnetic probe. The rms field is about 0.4 gauss, and shows only a slight attenuation at the highest density available. The observed decrease is consistent with a simple model of the penetration of an electromagnetic wave into a plasma below the plasma frequency. The wave damps according to

$$E = E_o e^{-x/\delta}$$

where δ is the penetration depth. The critical density n_c occurs when δ (= c/ω_p) is comparable to the dimensions of the plasma. The critical density for the electromagnetic case (1×10^{12} cm^{-3}) is much greater than for the electrostatic case (4×10^8 cm^{-3}). The electric field calculated from these data is about 1 V/cm, or two orders of magnitude less than obtained with the electrostatic drive at low densities. The important point, however, is that rf electric fields can be produced in low density plasmas even when the frequency is well below the plasma frequency. These data were obtained at low amplitude (5 watts) and linearly extrapolated up to the high power case.

Figure 4 shows a flux plot of the octupole field. At 1 MHz, ion cyclotron resonance occurs at about .7 kG, and if the heating follows the pattern of electron cyclotron heating, the heating should be maximum at places where the resonant B surface is tangent to a flux surface. The fields in the previous slide were measured at the resonance zone in the midplane near the inner wall.

An ion saturation current probe was placed on the B = 0 axis, and Fig. 5 shows the result. For the electrostatic drive, the current drops almost to zero when the heating pulse in applied. This result suggests that most of the plasma is swept out of the field by the large electric fields. Microwave diagnostics[3] confirm this fact. Optimistically, one could say that the heating was so effective that the magnetic field could not confine the energetic ions. The large negative floating potential during heating indicates that the ions are indeed preferentially lost. With the electromagnetic drive, the ion saturation current is nearly constant after heating. If the probe is moved out to the resonance zone and if the plasma is injected earlier to give it more time to cool, there is a substantial rise in ion saturation current. Since ion saturation current is proportional to density times the square root of ion temperature, one interpretation of this increase is that the ions are heated.

The percentage rise of ion saturation current was measured vs position across the midplane and the result is shown in Fig. 6. The rise is maximum near the walls at approximately the places where ion cyclotron resonance should occur. There is an uncertainty of several cm in the exact location of the resonances. This localized increase provides further evidence that some ion cyclotron heating is present.

A simple theory has been used to estimate the ion cyclotron heating rate.[2] The heating rate at a point is expressed in terms of the density n, perpendicular electric field $E_\perp$, and conductivity $\sigma_\perp$ by

$$\frac{dW_i}{dt} = \frac{1}{n}\frac{dP}{dV} = \frac{\sigma_\perp E_\perp^2}{n} \; .$$

The conductivity can be written in terms of a collision frequency ν as

$$\sigma_\perp \cong \varepsilon_o \, \omega_{pi} \nu \left[\frac{\omega^2 + \omega_{ci}^2}{(\omega^2 - \omega_{ci}^2)^2 + 4\omega^2\nu^2}\right] ,$$

and expanded in a Taylor series about the resonance at $\omega = \omega_{ci}$. For n constant everywhere within the cavity, the heating rate can be integrated over the volume of the machine to get an average ion heating rate:

$$\frac{d\overline{W}_i}{dt} = \frac{1}{nV} \int\!\!\oint \sigma_\perp E_\perp^2 \, \frac{d\ell}{B} \, d\psi = \frac{\pi e E_\perp^2}{2B_o} \left[\frac{B_o}{V}\frac{dV}{dB}\right]_{B_o} .$$

For an electric field of 1V/cm, the heating rate is about 0.1 eV/μsec. Since the electric fields obtained with the electromagnetic drive approach this value, we expect a small but definite heating. If the observed increase in ion saturation current is a result of ion heating, the heating rate is in approximate agreement with the theoretical prediction.

ACKNOWLEDGMENTS

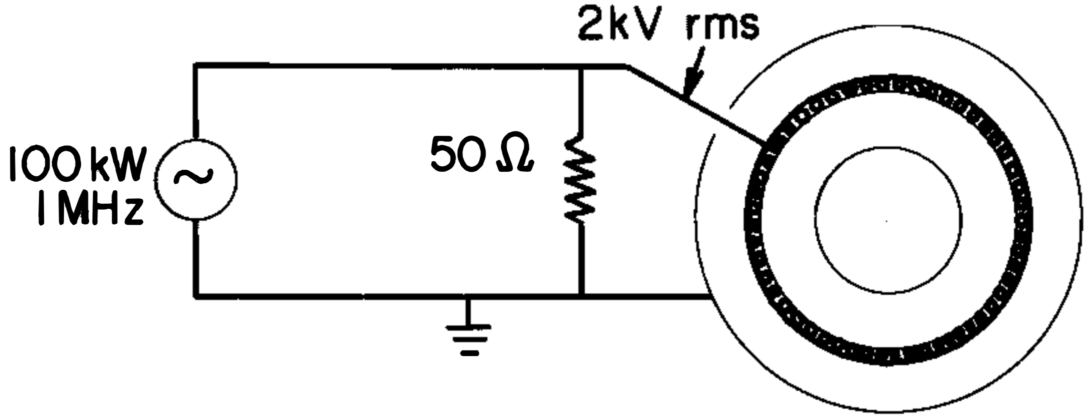
Some of the heating apparatus and diagnostics were constructed by Ron Parker. Glenn Kuswa provided helpful discussion, and made an attempt to measure the heating rate with an electrostatic analyzer. Work supported by U.S. Atomic Energy Commission.

REFERENCES

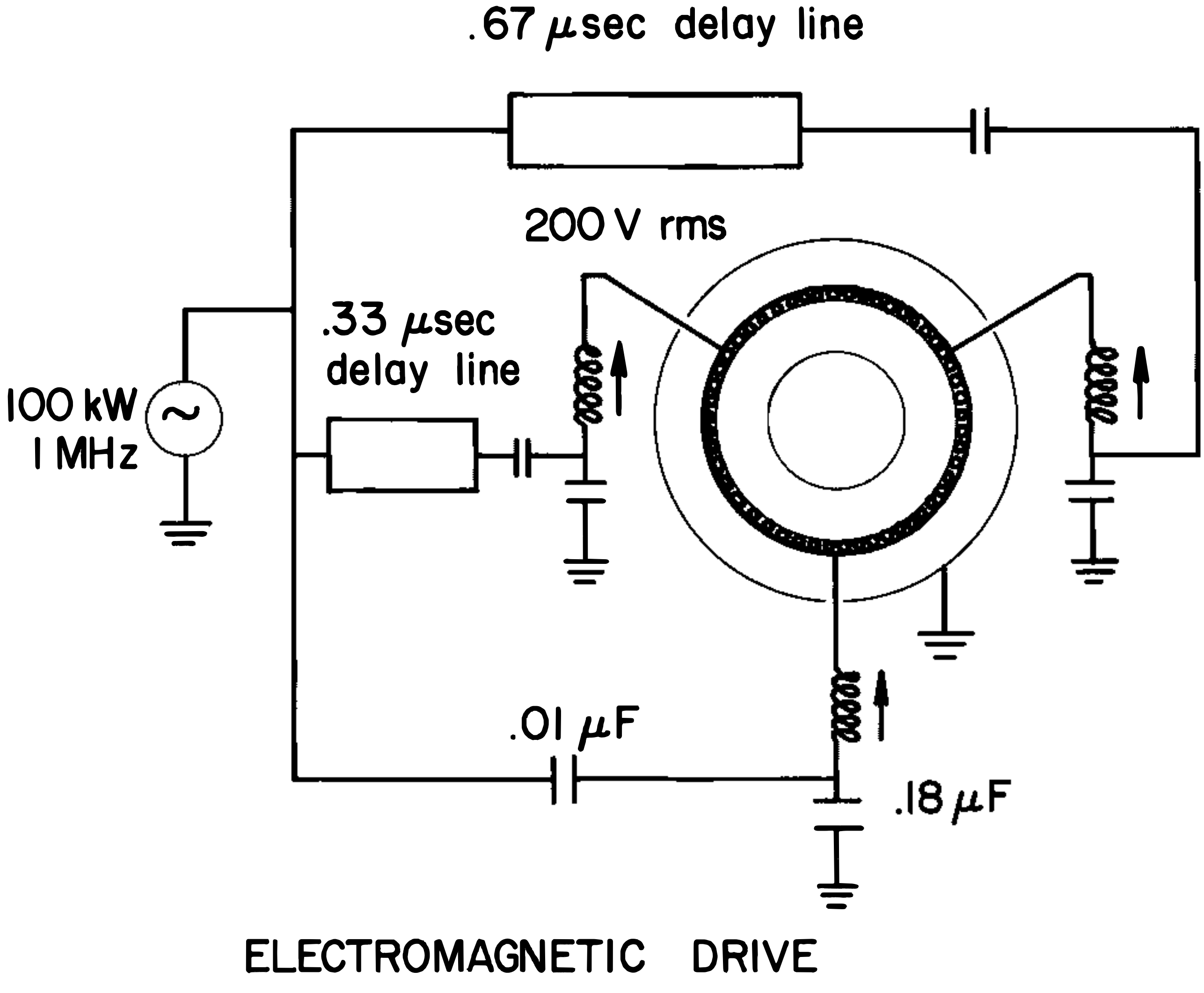
1. G.W. Kuswa, Bull. Am. Phys. Soc. 14, 1033 (1969).
2. J.C. Sprott, Univ. of Wisc. Ph.D. Thesis (1969).
3. J.W. Rudmin, private communication.

Figure Captions

1. Two methods for producing low frequency electric fields in the plasma.
2. RF potential across plasma for electrostatic drive.
3. Attenuation of rf field with increasing density for the two drive methods.
4. Flux plot showing constant B surfaces in the toroidal octupole
5. Oscilloscope traces showing the effect of rf heating as measured with Langmuir probes.
6. Fractional increase in ion saturation current vs distance across midplane for electromagnetic drive.



ELECTROSTATIC DRIVE



ELECTROMAGNETIC DRIVE

Figure 1

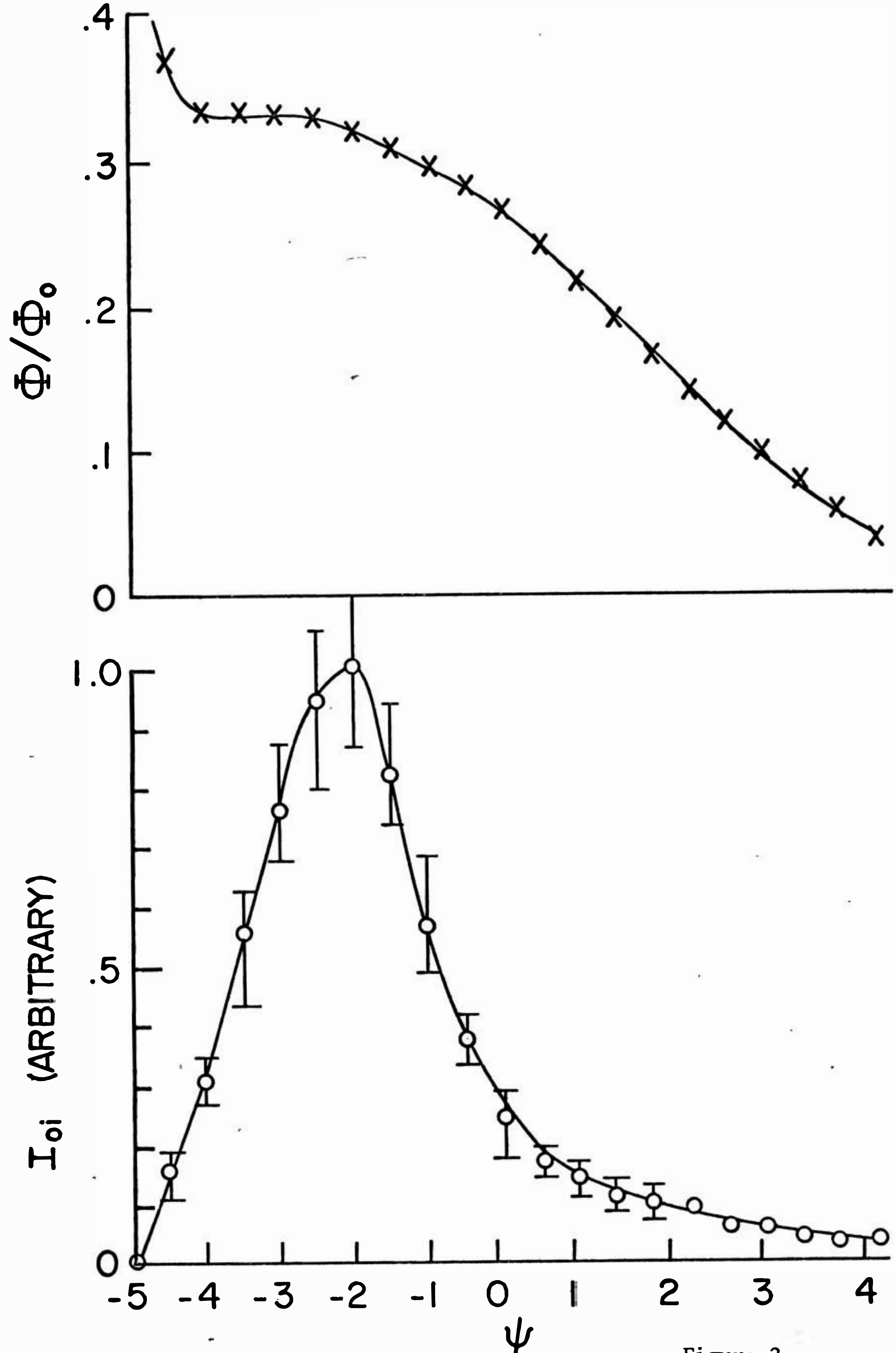
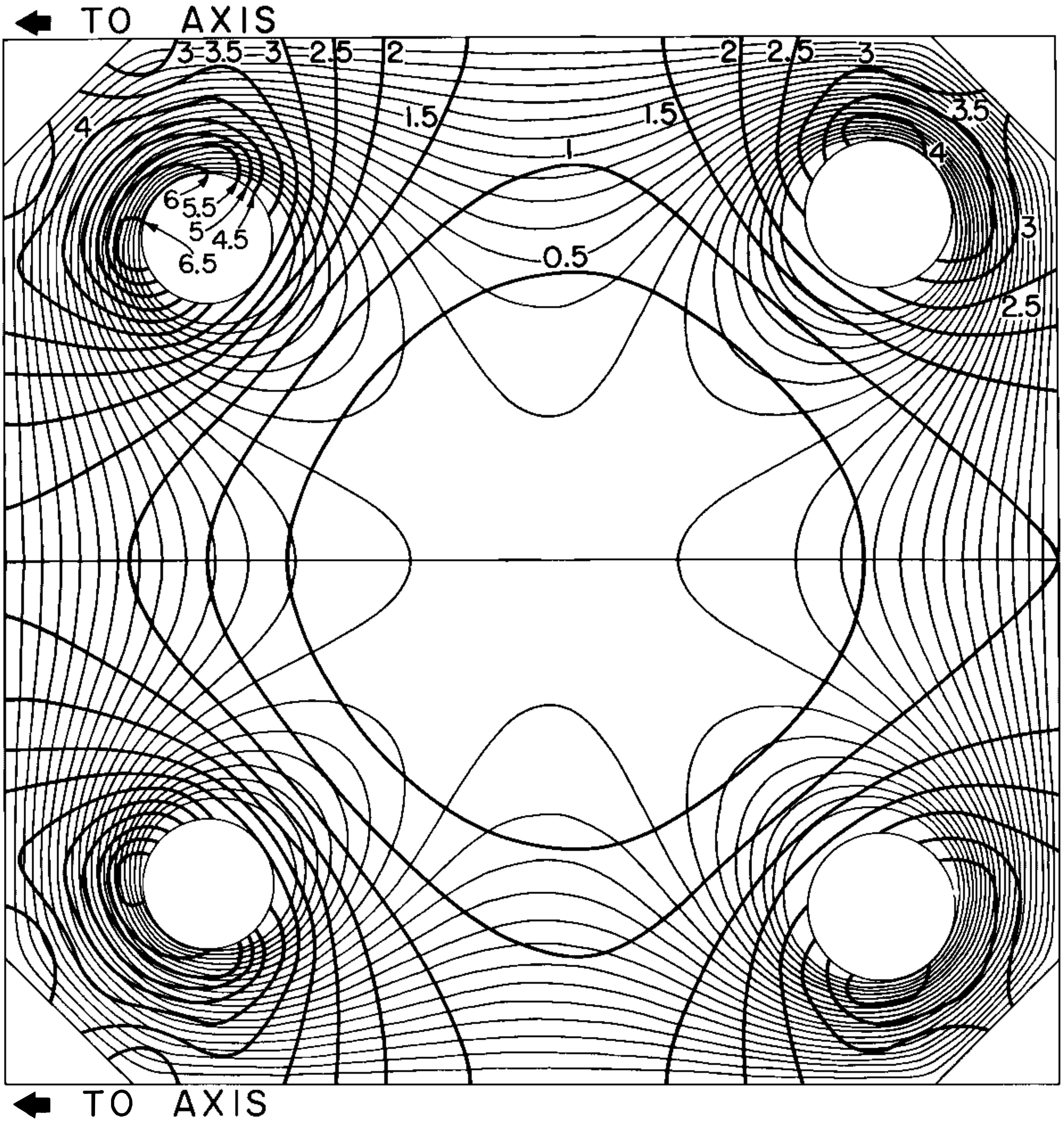


Figure 2



CONSTANT B SURFACES IN THE WISCONSIN TOROIDAL OCTUPOLE

Figure 4

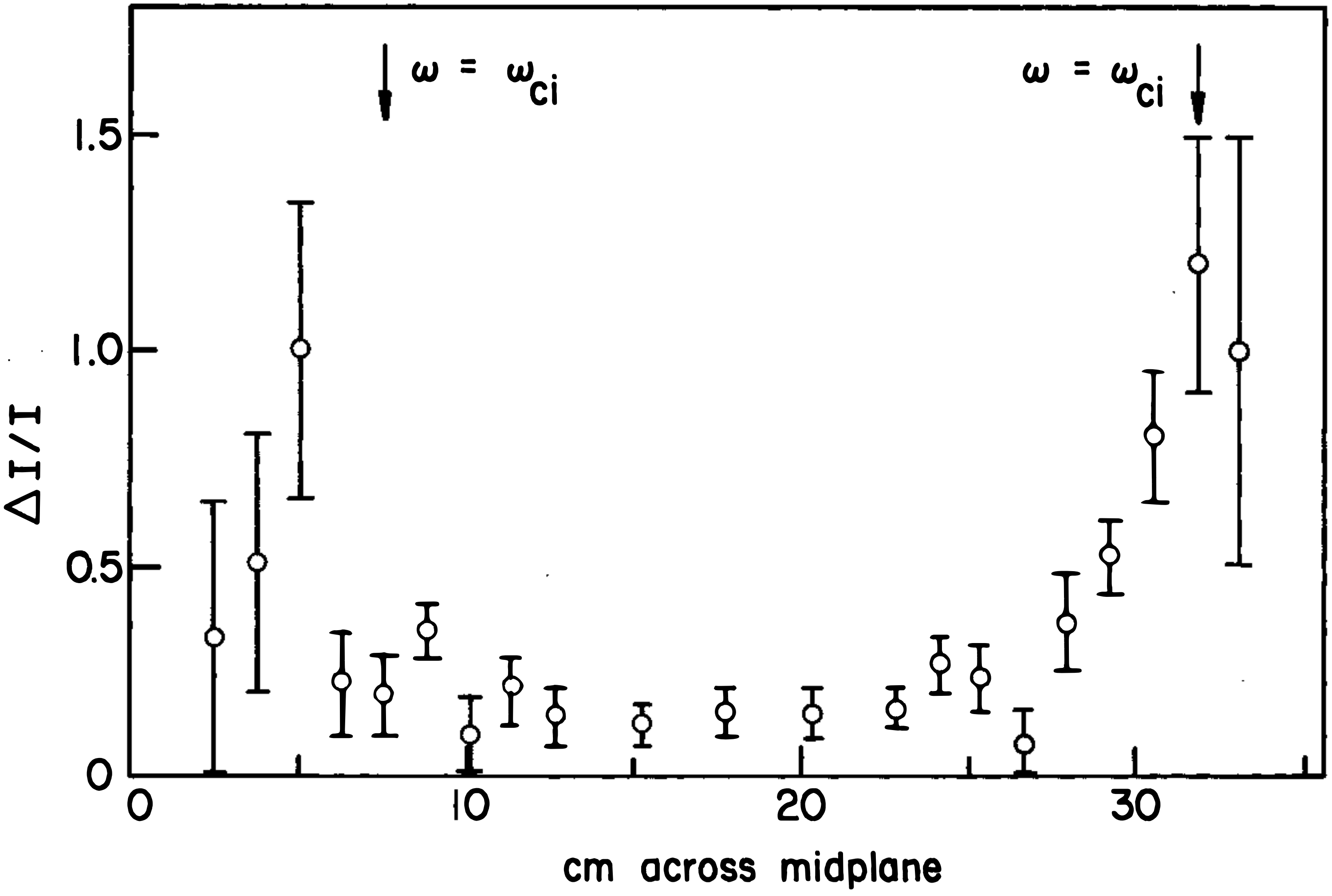
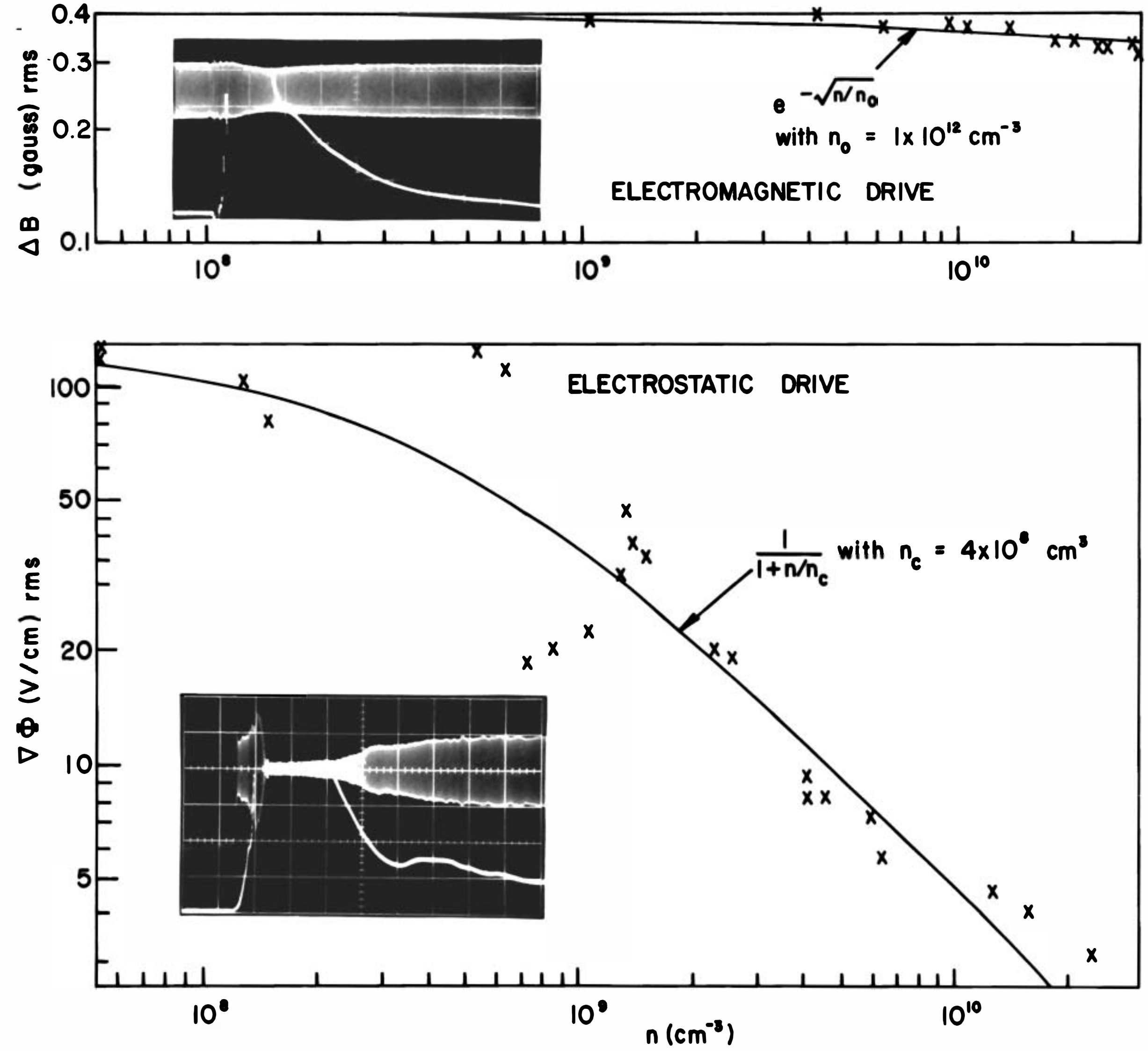

$\omega = \omega_{ci}$
$\omega = \omega_{ci}$
1.5
1.0
0.5
0
$\Delta I/I$
0
10
20
30
cm across midplane

Figure 6



ΔB (gauss) rms
0.4
0.3
0.2
0.1
$e^{-\sqrt{n/n_0}}$
with n_0 = 1x10^{12} cm^{-3}
ELECTROMAGNETIC DRIVE
10^8
10^9
10^{10}
∇Φ (V/cm) rms
100
50
20
10
5
ELECTROSTATIC DRIVE
$\frac{1}{1+n/n_c}$ with n_c = 4x10^8 cm^3
10^8
10^9
10^{10}
n (cm^{-3})

Figure 3

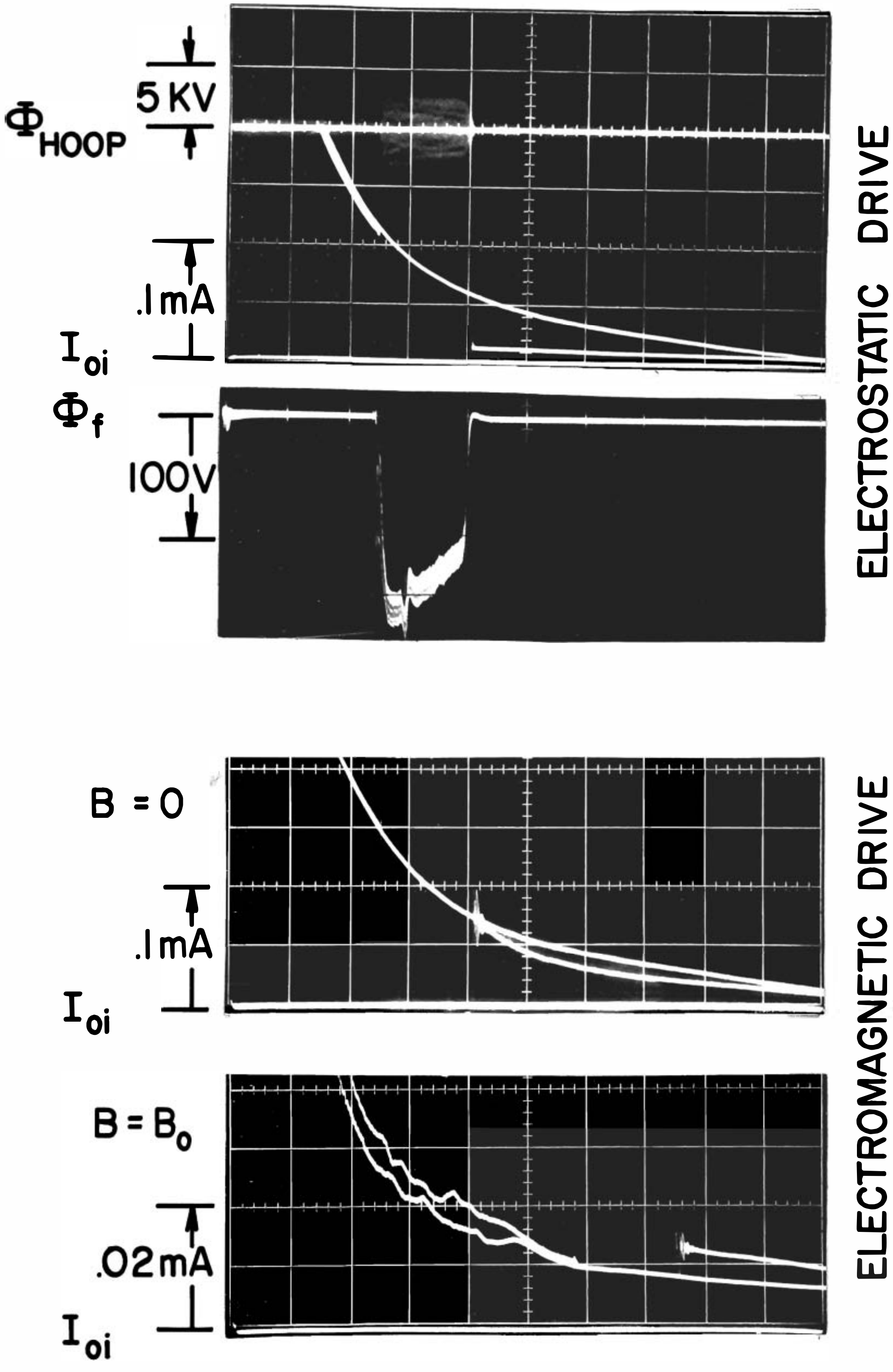

Φ_{HOOP}
5 KV
.1mA
I_{oi}
Φ_f
100V
ELECTROSTATIC DRIVE
B = 0
.1mA
I_{oi}
B = B_o
.02mA
I_{oi}
ELECTROMAGNETIC DRIVE

Figure 5